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Post-Rotatory Effects on Attitude Perception during Rolling Manoeuvre

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Executive Summary

Spatial disorientation has been identified as major causes of aviation accidents. One cause of spatial disorientation is an aftereffect of returning the body to a vertical posture after having maintained it for some time in a non-vertical posture. However, investigations into the nature of these aftereffects have frequently produced conflicting results. The experiments in Part A of the current study were designed to resolve several controversial issues by examining the effects of duration of body tilt and speed of return to vertical on the setting of a tactile rod to vertical. Judgments of tactile vertical became more erroneous as the duration of the adaptation tilt increased. Importantly, while tactile vertical was overestimated when subjects were held at the adaptation tilt, it was underestimated following their rotation back to vertical or 10° from vertical. This finding suggests that two distinct processes are involved in errors of the subjective vertical—one based on aftereffects of subjecting the otolith organs to a displaced direction of gravity and another based on aftereffects of rotary acceleration acting on the vestibular canals.

A second cause of disorientation in pilots arises from conflicts between information from the gravity sense organs and from vision. The experiments in Part B were designed to investigate the relative contributions of three frames of reference to judgments of self orientation to gravity. The first frame of reference is gravity, as sensed by the gravity sense organs (otolith and tactile/proprioceptive sense organs). The second frame of reference is the body axis and the third is the perceived tops and bottoms of familiar objects in the visual scene. I recently discovered that about 50% of adults feel upright in an upright room when in fact they are lying on the back looking at a wall of the room above them. This is similar to the situation in which a pilot in a banked or inverted aircraft feels upright in an upright aircraft. Experiment B1 was designed to measure the incidence of this type of reorientation illusion for each orientation of the body (erect, supine, prone, and recumbent) and each orientation of the visual surroundings. Reorientation illusions occurred in all condition except those in which the visual scene was upright. They occurred most often when the body was at the same angle to gravity as the visual scene, as when a pilot rotates with a rolling aircraft. There was very little evidence that people used their own body to judge the direction of gravity. There were large individual differences. Some people relied heavily on the visual scene while others relied on their gravity sense organs and ignored conflicting information from the visual scene.

We noticed that younger people were less prone to disorientation illusions and decided to investigate the effect of age. In Experiment B2 we determined the incidence of static and dynamic reorientation illusions in subjects ranging in age from 9 to 78 years. Ninety percent of subjects of all ages experienced the dynamic reorientation illusion when viewing a moving scene but the percentage of subjects experiencing static reorientation illusions increased with age. We propose

that the dynamic illusion depends on a primitive mechanism of visual-vestibular interaction but that static reorientation illusions depend on learned visual cues to the vertical arising from the perceived tops and bottoms of familiar objects and spatial relationships between objects. Older people become more dependent on visual polarity to compensate for loss in vestibular sensitivity.

PART A

AFTEREFFECTS OF BODY TILT ON THE PERCEPTION OF VERTICAL

Introduction

Aviation accidents are frequently attributed to spatial disorientation—the failure to perceive the position, attitude or motion of the aircraft (Cheung et al. 1995; Gillingham 1992; Navathe and Singh 1994). During slow banking/turning manoeuvres, aftereffects of tilt and rotation could be responsible for these errors. As a pilot's otolith organs are subjected to a displaced direction of gravity for a prolonged period, subjective vertical shifts in the opposite direction to the initial postural tilt—'otolith aftereffects'. The act of rolling the aircraft back to the horizontal could also produce 'vestibular canal aftereffects', which influence subjective vertical in the opposite direction to the roll motion. The present experiments examine judgments of tactile vertical while observers are held at an angle about the horizontal roll axis and then rolled to a lesser tilt angle.

Previous research has shown that exposure to periods of postural tilt can produce erroneous judgments of both gravitational vertical and body orientation. In these studies, subjects in darkness were held for a certain duration in an off-vertical posture about the roll or pitch axis. They then: (A) adjusted themselves until they felt vertical (Clark and Graybiel 1963; Fleishman, 1953; Mann and Passey 1951; Passey and Guedry 1949); (B) signaled when they felt that they had crossed the vertical (Clegg, 1954; Clegg and Dunfield 1954a, 1954b); (C) set a luminescent rod to their perceived body orientation (Bauermeister 1964; Ebenholtz, 1970; Tribukait et al. 1996); or (D) gave verbal estimates of perceived body orientation (Higashiyama and Koga, 1998). Results consistently showed that increasing the angle of the adaptation tilt increases the constant errors of judgments of vertical (Clegg and Dunfield 1954a; 1954b; Fleishman 1953; Mann and Passey 1951). However, the effect of the duration of the adaptation tilt varied from study to study. The procedures used in these earlier studies are summarized in Table 1.

Passey and Guedry (1949) performed the first study on the effect of adaptation tilt duration on judgments of body vertical. They found that constant errors of judgments of body vertical were greater after subjects had been held at a 10° adaptation tilt for 60s than when they were returned to vertical immediately. Similarly, Mann and Passey (1951) found that constant errors of judgments of body vertical increased as the duration of adaptation tilt increased in 5s steps from 0s to 65s. However, Clegg and Dunfield (1954b) failed to find a significant effect of tilt duration. In one of their experiments, subjects were tilted 15° for various time intervals between 0 and 105s, before being returned towards the vertical at 0.3°/s. Judgments of body vertical were not significantly different for any of these tilt durations. However, the slow return speeds may have reduced tilt aftereffects at the time of testing, which was 50s after the adaptation phase.

Study	Task	Tilt angle	Duration	Speed	Constant errors	Direction aftereffect
Mann et al. (1949	Return to vertical Signal when vertical	5° - 90° in 5° steps	0s	CW at 3°/s CWW at 2°/s	Return to vertical 1.1° Signal when vertical 4°	Vertical underestimated
Man & Passey (1951)	Return to vertical	5° – 55° in 5° steps	0.5s to 65s	Variable	Increased with duration, 2.7° to 4.4°	More under than over estimation of vertical
Fleischman (1953)	Return to vertical	15°, 20°, 25°	5s	Out: 4, 5 or 6°/s. Back: same or different	Decreased with return speed, 2.2° to 1.7°. Increased with tilt, 1.5° to 2.6°	Vertical underestimated
Clegg & Dunfield (1954)	Signal when vertical	15°	15s	Out: 0.2°/s Back: 0.05 to 0.6°/s	Decreased with return speed, 3.5° to 0.3°	Vertical underestimated
Bauermeister (1964)	Set rod vertical	0° - 90°in 10° steps	Time to set rod	Did not return	Increased with tilt, 0.1° to 17°	Body tilt overestimated
Ebenholtz (1970)	Set rod vertical	0° - 90° in 15° steps	180s	Did not return	Increased with tilt, 0.1° to 14°	Under 45° overestimated. Larger tilts underestimated
Schöne & Lechner-Steinleitner (1978)	Set rod vertical	0°, 45°, 90°	6 minutes	Not specified	Not reported	Vertical underestimated
Tribukait et al. (1996)	Set rod horizontal	0°, 10°, 20°, 30°	2 minutes	Did not return	Increased with tilt, 0.1° to 5.9°	Large tilts overestimated
Higashiyama & Koga (1998)	Estimate body tilt	72°. Then rotated to between –18° and +108°	10 minutes	Out: 5°/s. Back: not specified	Increased with deviation from initial tilt. Means not provided	Small tilts underestimated. Large tilts overestimated

Table 1. Summary of results of previous studies on the aftereffects of body tilt.

Another controversial issue is the direction of these 'tilt aftereffects. As mentioned above, many previously reported errors of the subjective vertical may have been due not only to aftereffects of tilt, but also to aftereffects of rotation. In general, studies in which subjects 'returned to the subjective vertical' or 'signaled when they crossed the subjective vertical' found consistent underestimations, that is, errors in the direction of the adaptation tilt. (Clark and Graybiel 1963; Clegg and Dunfield 1954a; 1954b; Fleishman 1953; Mann et al. 1949; Mann and Passey 1951; Passey and Guedry 1949). Conversely, studies in which subjects set a luminous visual object to the apparent vertical or horizontal tended to find overestimations (Bauermeister, 1964; Ebenholtz 1970; Higashiyama and Koga 1998; Ito and Gresty 1996; Tribukait et al 1996). While the results of these results suggest that different dependent measures might produce different direction errors, there are exceptions to the above—for example Schöne and Lechner-Steinleitner (1978) found underestimations using a visual rod.

EXPERIMENT A1

Effect of Tilt Duration on Judgments of Vertical

This experiment examined the effect on perceived tactile vertical of holding the body at a roll angle of 45° for periods of 0, 30, 60 or 90s. Unlike earlier studies on tilt duration, for example, Clegg and Dunfield (1954b), the delay between adaptation and test phases was always brief—ranging between 6.7s and 15.1s—depending on the speed of the subject's return to the final body orientation (vertical or 10° to left or right of vertical). During the test phase, judgments of vertical were measured continuously with an unseen tactile rod for 60s. This dependent measure removed any extraneous visual cues to gravitational vertical and allowed us to examine the time course of the tilt aftereffect.

Method

Subjects

Seven subjects (six males and one female) participated in this experiment. Six of these were naive as to the purpose of the experiment.

Apparatus

The subject was secured with a five point harness in a chair that could be rotated in the roll plane. A safety switch prevented the chair tilting more than 50°. Head, shoulder, arm and knee pads attached to the chair minimized changes in pressure acting on the body during rotation. The chair's position (with an error of less than ±0.5°) and velocity profile were controlled by an IBM PC containing a DMC 620 card. A rod with a knob on one end and pivoted about its centre was supported 30cm in front of the subject. Subjects responded by turning the rod until the end with the knob was judged to be pointing down. A computer sampled the position of the rod every 100th of a second throughout the 60s test period.

Procedure

The subject was kept in complete darkness throughout the experiment. Each trial involved the following. The subject was initially seated in the vertical chair. The chair was then rotated 45° about the subject's roll axis at a constant speed of 5°/s. The horizontal axis passed approximately through the body's centre of gravity. The direction of rotation (clockwise or counterclockwise) was determined randomly. The subject was held at the tilt position for one of four durations (0s, 30s, 60s, or 90s), before being returned at one of three speeds (3.9°/s, 5°/s, or 6.1°/s) to the final position for the trial (vertical or 10° to the left or right of vertical). The subject then set the tactile rod to the

direction of gravity over a period of 60s. Rotations of the subject to or from the adaptation tilt position had a trapezoidal velocity profile with each acceleration and deceleration period lasting 1s. Each subject performed two repetitions of 36 conditions in four sessions of 18 trials, with each session on a different day.

Data Analysis

Tactile rod recordings for each trial were averaged within the following three time intervals: 0-19s, 20-39s, and 40-60s after the subject had returned from the adaptation tilt to the final body position. Underestimations (in the direction of the adaptation tilt) were negatively signed and overestimations were positively signed. Results were averaged over the three final body positions (0° or 10° to the left or right of vertical) since the these were used only to obscure the direction of gravitational vertical at test. This provided a total of six replications of each of the twelve experimental conditions—two sets of 60s tactile rod readings taken at three final positions.

Results

The initial errors (0-19s) for each of the seven subjects are shown in Table 2. Error magnitude increased in a linear fashion with the duration of adaptation tilt [F (1,6) = 32.8, $p < .003$]. This linear effect was still significant 20-39s [F (1,6) = 23.8, $p < .003$] and 40-60s [F (1,6) = 23, $p < .003$] into the test phase (see Figure 1).

Tilt Duration	Constant Error	S.D.
0s	-2.94°	8.84°
30s	-5.65°	8.83°
60s	-7.96°	11.02°
90s	-10.59°	11.28°

Table 2. Constant errors and standard deviations of the initial estimates of tactile vertical as a function of the duration of tilt adaptation. Negative signs indicate errors in the direction of the adaptation tilt.

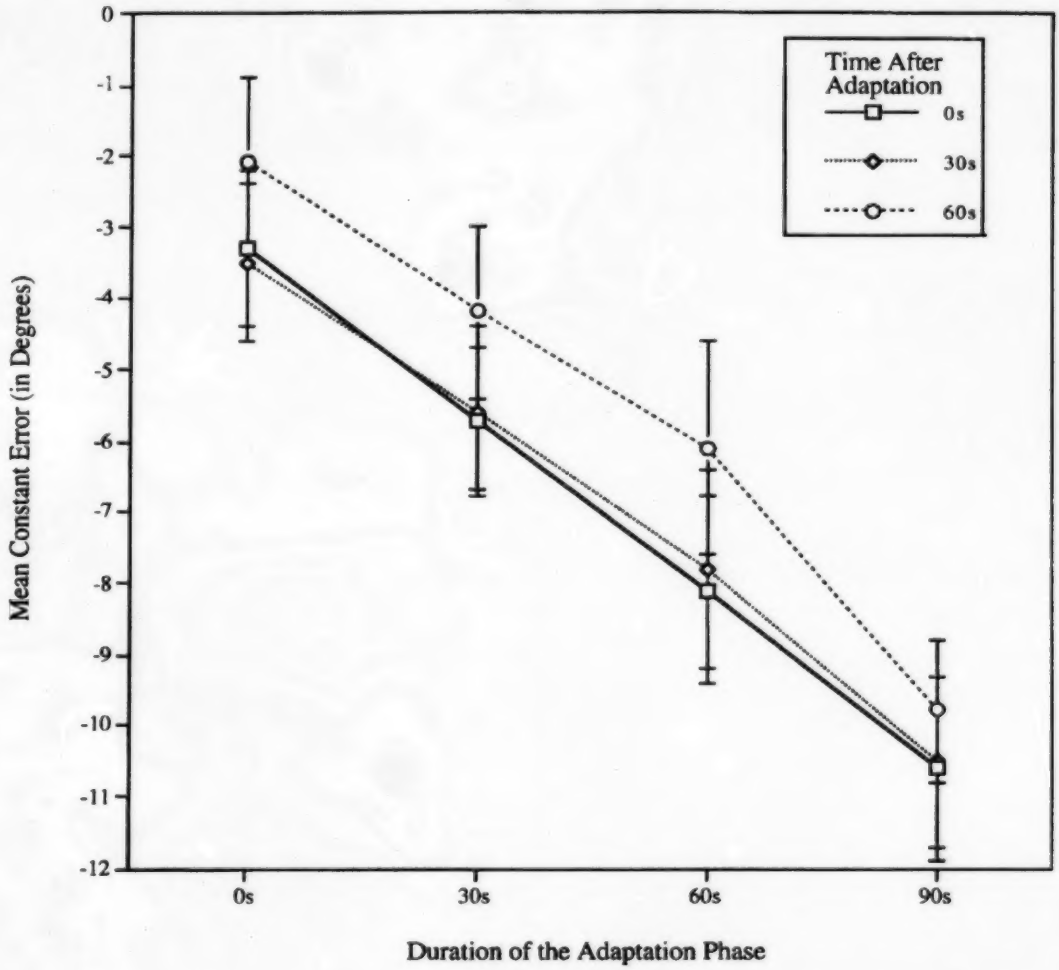

Figure 1. Mean constant errors of estimates of tactile vertical as a function of the duration of the adaptation phase. The plot shows mean errors recorded over three time intervals: 0-19s, 20-39s, and 40-60s after the adaptation phase. Error bars represent standard errors of the means.

Over the narrow range of speeds tested (3.9-6.1°/s), there was no significant effect of return speed on the constant errors at 0-19s [F (2,12) = .701, $p > .05$ - see Table 3] or 40-60s into the test period [F (2,12) = 2.4, $p > .05$]. However, there was a significant effect of return speed on constant errors 20-39s into the test phase [F (2,12) = 4.3, $p < .04$]. Specifically, the two fastest return speeds (5 and 6.1°/s) produced significantly greater constant errors than the slowest return speed (3.9°/s) [F (1,6) = 6.4, $p < .03$].

Return Speed	Constant Error	S.D.
3.9°/s	-5.8°	9.3°
5°/s	-6.8°	8.9°
6.1°/s	-7.8°	11.3°

Table 3. Constant errors and standard deviations of the initial estimates of tactile vertical for three return speeds. Negative signs indicate errors in the direction of the adaptation tilt.

Overall, constant errors of tactile vertical were not significantly different between any of the time intervals tested (0-19s, 20-39s, or 40-60s into the test phase - F(2,12) = 2.5, $p > .05$).

Discussion

Consistent with the early research (Passey and Guedry 1949; Mann and Passey, 1951) judgments of tactile vertical became more erroneous as duration of adaptation tilt increased from 0s to 90s. These errors increased in a linear fashion as subjects were held at the adaptation tilt of 45° for progressively longer periods. The current results conflict with those of Clegg and his associates (Clegg 1954; Clegg and Dunfield 1954a; 1954b), who found that the duration of a 15° adaptation tilt did not significantly affect judgments of body vertical. In the introduction, it was proposed that this finding might have been due to the 50s delay between adaptation and test phases, which could have reduced tilt aftereffects. While the current experiment found that strong tilt aftereffects were still present 60s after the adaptation phase, this proposal could still be valid if it is assumed that the angle of the adaptation tilt interacts with its' duration to determine the size/persistence of the tilt aftereffect. For example, an adaptation tilt of 45° might produce an aftereffect that persists longer than one of 15°.

The current study found that errors of tactile vertical (20-39s after reaching the final position) increased with the return speed from 3.9°/s to 6.1°/s. Clegg and Dunfield (1954b), however, found

the opposite pattern of results - errors of body vertical decreased as the return speed increased from 0.06°/s to 0.6°/s. This discrepancy might have been due to either the much faster return speeds used in the current experiment, its' larger adaptation tilt angle (45° as opposed to 15°), or its' different dependent measure (setting a tactile rod to vertical as opposed to signaling when the chair had crossed the vertical).

Another finding of interest was that no reduction in the magnitude of errors of tactile vertical occurred over the three time intervals tested (0-19s, 20-39s, and 40-60s). To our knowledge, this paper is the first to examine continuous recordings of subjective vertical following periods of tilt adaptation. Accordingly, the persistence of these errors could have been the result of a number of factors. One possibility is that setting a tactile rod is a fairly coarse measure of the subjective vertical, which obscured any decay in tilt aftereffects. However, this possibility appears unlikely, since tactile rod settings in this experiment were sensitive to reasonable variations in both tilt duration and speed of return. Another possibility is that subjects were reluctant to alter their initial tactile rod settings later in the test phase. The final possibility was that the current results indicate that tilt aftereffects decline slowly over long time intervals.

While recent studies using visual rods and lines have tended to produce overestimations of the subjective vertical (Bauermeister 1964; Ebenholtz 1970; Ito and Gresty 1996; Tribukait et al. 1996). the current study found that tactile rod settings consistently underestimated the direction of gravity (errors were in the direction of the adaptation tilt). This finding is consistent with data obtained in studies using 'return to the vertical' or 'signal when cross the vertical' tasks (Passey and Guedry 1949; Mann and Passey 1951; Fleishman 1953; Clegg and Dunfield 1954a; 1954b). The current study had a number of procedural differences which could account for its discrepant findings relative to previous 'rod setting' studies. First, while subjects in earlier studies used *visual* rods to estimate either vertical or their body orientation in an otherwise dark room, subjects in the current study used a *tactile* rod to estimate gravitational vertical. Thus, it is possible that while observers overestimate vertical and body orientation using visual rods, they underestimate these attributes using tactile rods. Second, while subjects in previous studies made their visual rod settings at the adaptation tilt, subjects in the current study were rotated to a position at or around vertical before making their tactile rod settings. This possibility is discussed further below.

EXPERIMENT A2

Effect of Tilt Angle and Return Speed on Tilt Aftereffects

Experiment 1 demonstrated that errors of tactile vertical increase with the duration of body tilt. However, these errors may have been due in part to vestibular canal aftereffects, as they were obtained directly after observers were restored to vertical or near vertical. Experiment 2 examined this possibility. Judgments of tactile vertical were obtained continuously during the 60s adaptation phase when the subject was tilted 20° and in the subsequent 60s test phase after the subject had been returned to vertical or near vertical. If vestibular canal aftereffects contribute to errors of the subjective vertical, then the directions of these errors might be different at adaptation and test, since rotations to the initial tilt and to the final position were in opposite directions.

This experiment also reexamined the effect of return speed on tactile vertical. While Experiment 1 found that errors of tactile vertical increased with return speed, Clegg and Dunfield (1954b) had found that errors of body vertical decreased as return speed increased. Experiment 2 used smaller adaptation tilt angles (20° as opposed to 45°) and a wider range of return speeds (0.5 - 5°/s as opposed to 3.9 - 6.1°/s) than used in Experiment 1. These experimental conditions were similar to those used by Clegg and Dunfield (adaptation tilts of 15° and return speeds between 0.06°/s to 0.6°/s).

Method

Subjects

Seven subjects (five males and two females) participated in this experiment. Six subjects were naive as to the purpose of the experiment.

Procedure

As in Experiment 1, subjects were kept in complete darkness throughout the experiment. They were instructed to keep the tactile rod pointing in the direction of gravity at all times. In each trial the subject was rotated clockwise or counterclockwise at a constant speed of 5°/s to a tilt of 20°. The horizontal axis of rotation passed approximately through the subject's centre of gravity. The subject was held at that position for 60s, before being returned at one of three speeds (0.5°/s, 2°/s, or 5°/s) to the final position for the trial (0° or 10° to the left or right of vertical). All rotations of the subject had a trapezoidal velocity profile with each acceleration and deceleration period lasting 1s.

Data Analysis

Tactile rod settings at the adaptation tilt were averaged within each of three time intervals (0-19s, 20-39s, and 40-60s) after the subject had been tilted and again after the subject had been returned to

vertical or near vertical. Underestimates (in the direction of the adaptation tilt) were negatively signed and overestimates were positively signed. Results were averaged over the three final positions and the two directions of tilt, this providing a total of six replications of each experimental condition.

Results

Judgments of tactile vertical made at the adaptation tilt (20°) were significantly different from those made at the final position (0° or 10°) are shown in Figure 2. Settings at these two positions were significantly different [$F(5,30) = 23.36$, $p < .001$]. Specifically, tactile vertical was overestimated at the adaptation tilt (see Table 4) and underestimated after the subject was returned to a lesser test tilt (see Table 5).

Time Elapsed in Adaptation Phase	Mean Constant Error	S.D.
0-19s	4.4°	8.0°
20-39s	4.7°	9.0°
40-60s	4.4°	10.5°

Table 4. Constant errors and standard deviations of the estimates of tactile vertical during the adaptation phase. Positive signs indicate errors in opposite the direction to the adaptation tilt.

Time Elapsed in Test Phase	Mean Constant Error	S.D.
0-19s	-4.7°	7.2°
20-39s	-5.2°	7.9°
40-60s	-5.3°	7.0°

Table 5. Constant errors and standard deviations of the estimates of tactile vertical during the test phase. Negative signs indicate errors in the direction of the adaptation tilt.

Figure 2 shows that constant errors of tactile vertical at the final position decreased as return speed increased from 0.5°/s to 5°/s. This result is consistent with those from Clegg and Dunfield's study. Errors produced by a return speed of 0.5°/s were larger than those produced by return speeds of 2°/s or 5°/s at all three time intervals [$F(1,6) = 4.17$, $p < .05$; $F(1,6) = 6.15$, $p < .02$; $F(1,6) = 4.32$, $p < .04$]. However, errors produced by a speed of 2°/s were not significantly

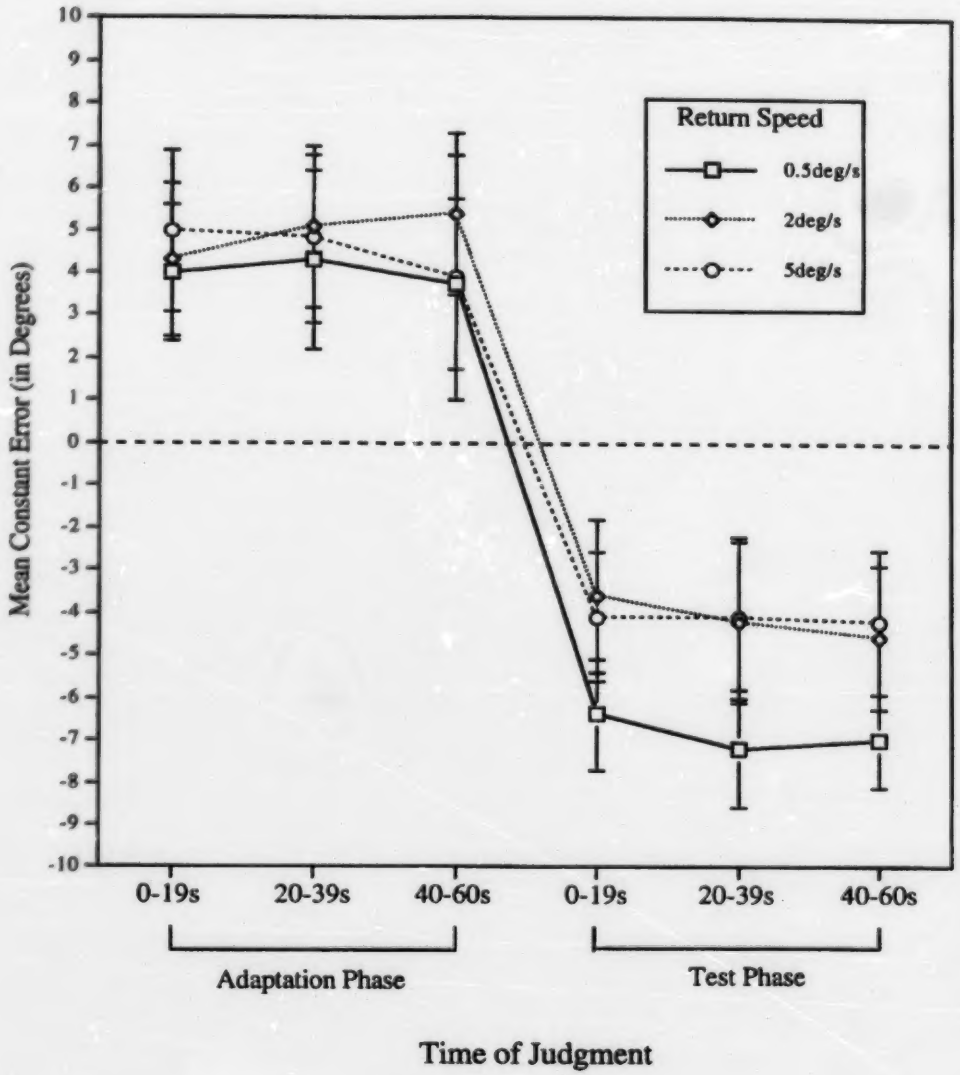

Figure 2. Mean constant errors of estimates of tactile vertical as a function of the tilt of the subject, the time elapsed at each tilt and return speed (0.5°/s, 2°/s and 5°/s). Errors are shown at: (1) 0-19s, 20-39s, and 40-60s into the adaptation phase; and (2) 0-19s, 20-39s, and 40-60s into the final test phase. Error bars represent standard errors of the means.

different from those produced by a speed of 5°/s at any of these time intervals [F (1,6) = .13, p > .05; F (1,6) = .10, p > .05; F (1,6) = .09, p < .05)].

Constant errors of tactile vertical did not vary significantly with time at the adaptation tilt [F(1,6) = .007, p > .05]. As in Experiment 1, constant errors of tactile vertical did not vary significantly with time at the final position [F (1,6) = .18, p > .05].

Discussion

This experiment found that tactile vertical was overestimated when the subject was at the adaptation tilt and underestimated when the subject was returned to a lesser test tilt. There are several possible explanations for this finding. One possibility is that the direction of the tilt aftereffect changes over time. According to this notion, errors of tactile vertical were initially overestimates and as time passed they diminished and eventually, after 60s, they became underestimates. However, data from Experiment 1 do not support this notion, since initial errors at the vertical test position after 0 and 30s of tilt adaptation were underestimates rather than overestimates. Another possibility is that the direction of these errors depends on the subject's physical orientation at the time of estimation. For example, reducing the subject's tilt from '20° right' to '10° left' or from '20° left' to '10° right' could have led to tilt aftereffects in opposite directions. However, such effects should not have been present in the data, since trials in which body tilt was reduced from '20° right' to '10° right' and those in which it was reduced from '20° left' to '10° left' were counterbalanced. Thus, the most likely explanation for the directional difference found in Experiment 2 is that rotating the observer either to the adaptation tilt or later to the final position produced a vestibular canal aftereffect which interacted with the otolith aftereffect. Errors of the tactile vertical at the adaptation tilt would be due initially to aftereffects of rotation (as negligible tilt adaptation would have occurred) and later to a combination of rotational and tilt aftereffects. According to this explanation, overestimates were produced by rotation towards the adaptation tilt angle and underestimates were produced by rotation away from the adaptation tilt to the final position for that trial. These errors were then modified by otolith aftereffects in a time dependent manner.

In agreement with the results from the Clegg and Dunfield (1954b) study, we found that constant errors of the tactile vertical decreased as return speed increased from 0.5°/s to 2°/s. However, further increasing return speed from 2°/s to 5°/s did not have a significant effect on these errors. This would appear inconsistent with the finding of Experiment 1 that errors of the tactile vertical increased as return speed increased from 3.9°/s to 6.1°/s. However, it is possible that return speed interacted with return displacement to determine the magnitude of these constant errors. Return displacements in Experiment 1 ranged from 35° to 55° whereas those in Experiment 2

ranged from 10° to 30°. A more likely possibility is that while the slowest return speed used in Experiment 2 produced large errors because it was below the threshold for vestibular detection[2], the fastest return speed used in Experiment 1 produced large errors because it produced strong canal aftereffects. According to Gundry (1978) a rotation about a horizontal axis at $0.5°/s^2$ should take longer than 1s (the time taken to accelerate the chair to its constant return velocity) in order to be detected.

General conclusions from Part A

The current findings resolve a number of controversial issues in the literature. The results of Experiment 1 show conclusively that errors of tactile vertical increase in a linear fashion with the duration of the adaptation tilt. The results of Experiment 2 show that while tactile vertical was overestimated at the adaptation tilt, it was underestimated after the observer had been rotated back to 0° or 10° off vertical. Taken together, these results suggest that two distinct processes are involved in errors of the subjective vertical—one based on aftereffects of subjecting the otolith organs to a displaced direction of gravity, and the second based on aftereffects of rotary acceleration acting on the vestibular canals. In particular, it appears that the act of rotating the observer either initially to the adaptation tilt or later to the final test position for that trial produced a vestibular canal aftereffect which interacted with the otolith aftereffect to determine the direction of errors of tactile vertical. This explanation reconciles the apparently contradictory results in the previous literature on the direction of the tilt aftereffect. According to this notion, earlier studies using visual rods and lines produced overestimates because judgments were almost always made when observers were at the adaptation tilt. However, studies where observers returned themselves to the vertical or signaled when they crossed the vertical found underestimates due to canal aftereffects produced by rolling the observer towards the final position.

From the results of Experiment 2, it can be seen that tactile vertical tends to shift in the opposite direction to the preceding rotation. Errors of the tactile vertical were in the opposite direction to the adaptation tilt (overestimates) following rotation away from the vertical to the adaptation tilt. Conversely, errors of tactile vertical were in the direction of the adaptation tilt (underestimates) following rotation back from the adaptation tilt towards the vertical. Melvill-Jones et al. (1964) proposed that velocity signals from the vestibular canals may be integrated to an angular displacement signal. This could explain the effect of rotation direction on errors of tactile vertical. According to this notion, during prolonged rotation, the observer's apparent angular velocity declines as the cupula returns to its resting position and neural aftereffects subside, resulting in an underestimation of self displacement. Hence, this theory predicts that estimates of body orientation

based on inputs from the canals should be shifted in the opposite direction to the observer's rotation.

Our results suggest that return speed plays a complex role in the perception of tactile vertical. In Experiment 2 we found that for slower return speeds (0.5-2°/s) errors of tactile vertical decreased as the speed of rotation increased. This was presumably because, as rotational speed increased within this range, it eventually reached the threshold for detection. Conversely, in Experiment 1, for faster return speeds (3.9-6.1°/s) errors of tactile vertical increased with return speed—presumably due to these increasingly higher speeds of rotation producing correspondingly larger canal aftereffects. Thus, on the basis of these findings, both very slow and very fast return speeds would be expected to produce the most erroneous judgments of vertical.

In conclusion, the duration of the adaptation tilt and the speed of observer rotation both have important consequences for the subjective vertical. Importantly, errors of the subjective vertical persist with little reduction in magnitude for substantial periods at both the adaptation tilt and the final position (>120s). Hence, tilt and canal aftereffects would appear to pose a serious problem for certain aviation manoeuvres, such as slow banking turns. One potential solution may lie in the fact that these errors tend to occur in the direction of the adaptation tilt as the pilot reduces the bank angle. An awareness of this directional bias may help overcome accidents based on tilt and roll aftereffects in the future.

PART B

REORIENTATION ILLUSIONS INDUCED BY VESTIBULAR-VISUAL CONFLICT

Introduction

An example of serious pilot error caused by confusion of visual frames of reference to the direction of gravity is provided by the graveyard spiral. The conventional artificial horizon in an aircraft cockpit remains parallel to the ground as the plane banks. However, the interior of a banking aircraft is perceived as vertical. Therefore, the artificial horizon appears to move with respect to the perceptually fixed line representing the aircraft. When an aircraft suffers a sudden and unexpected change in attitude the pilot may confuse the two visual lines and try to bring the horizon line level back to the perceived horizontal. This increases rather than increases the bank angle and sends the aircraft into a fatal spiral dive (Roscoe 1997). Some pilots tilt the head when banking so as to keep the artificial horizon (and the true horizon) orthogonal to the head (Patterson et al. 1997). This should help for a simple roll manoeuvre because the hair cells of the otolith organs will not be displaced. However, in a banked turn, the direction of the resultant gravito-inertial force acting on the body remains orthogonal to the floor of the aircraft so that tilting the head under these circumstances deflects the hair cells. Another factor is the extent to which a pilot tends to perceive the direction of gravity in terms of when his feet are. In Russian aircraft, the line representing the aircraft rotates relative to a artificial horizon that remains fixed with respect to the aircraft. The effects of these factors on the incidence of pilot disorientation will depend on the relative weighting that a pilot gives to information from the gravity sense organs, vision, and the body axis in perceiving the direction of gravitational 'down'. The Experiments in Part B are designed to investigate how people weight conflicting information from these three sources.

Judgments of the orientation of the self to gravity can be made with respect to each of three frames of reference: the visual frame, gravity, and the longitudinal body axis (Friederici and Levelt 1987). Normally, the three frames of reference are aligned but, when they are not aligned, judgements usually depend on weighted contributions from each of the three frames of reference. (1) **The gravitational frame of reference,** in purely physical terms, is the direction of gravity. The direction of gravity can be detected only by sense organs sensitive to the magnitude and direction of gravito-inertial forces. These are the otolith organs, tactile receptors, and proprioceptors. Such sense organs cannot distinguish between changes due to linear acceleration, changes due to body tilt and changes due to centrifugation. Therefore, the *sensory gravitational frame of reference* is the resultant direction of the inertial forces acting on the body. But the direction of inertial forces may be misregistered, so that the *perceptual gravitational frame of reference* is the perceived direction of inertial forces. This is the only inertial frame of reference available to a person. Nevertheless, we

will use the *physical gravitational frame of reference*. Thus, the direction of the signed longitudinal axis of the body with respect to gravitational down defines the gravitational orientation of the body.
(2) **The visual frame of reference** has two components. The first is the basic frame defined by the main orthogonal lines and surfaces in a scene or by an axis of symmetry. Judgments of self orientation are affected by a frame tilted with respect to gravity. A square frame can be used for judgments of the orientation of the self only up to 90°, or only to 45° if the diagonal axis of symmetry is accepted as vertical. A simple frame does not indicate which way is 'up' and which way is 'down'. The orientation of the self to the visual frame is a vector with 90° or 45° periodicity.

The second component of the visual frame of reference is the axis of visual polarity. We distinguish between two types of visual polarity; intrinsic polarity and extrinsic polarity. An object has intrinsic polarity when it contains an identifiable axis with one end perceptually 'top' and the other end perceptually 'bottom'. A polarity axis is usually an axis of symmetry. Animals, houses, tables, and cars have a plane of bilateral symmetry with a 'top' and a 'bottom'. Trees and domes have radial symmetry about a central axis with a 'top' and 'bottom'. The polarity axis of an object is usually vertical and, when it is not vertical, the object usually appears tilted or inverted to an erect observer. An axis of extrinsic polarity is defined by spatial relationships between objects. An object supported on another object, such as a box on a shelf, a falling object, and an object hanging on a string possess an extrinsic axis of polarity.

These visual frames are defined physically but they correspond closely to perceived visual frames. This is because people are very accurate in registering the visual directions of lines and axes, as reflected in their ability to set a test line parallel to another line. We will consider only cases in which the visual frame, and the axes of intrinsic and extrinsic polarity are aligned. We define the orientation of the visual-frame as the angle between the visual polarity axis and the direction of gravity.
(3) **The body-axis frame of reference** is the longitudinal axis of the body with head signifying 'up' and feet signifying 'down'. Mittelstaedt (1983, 1986) called it the idiotropic vector. Theoretically, it has at least three components: the normally vertical retinal meridians, the z axis of the head, and the z axis of the trunk. However, we shall consider only the unitary frame of the body as a whole. Mittelstaedt (1983) argued that, "...the idiotropic vector is not part of a specific sensory system but rather a central nervous agent." It does not require external stimulation but it is difficult to see how it could operate in a person with all senses anaesthetized and all motor systems paralyzed. Its operation is most evident in astronauts floating in space when they perceive 'down' as being where their feet are.

The idiotropic frame is defined physically, but it corresponds closely to the perceived direction of the body axis. Thus, erect subjects can set a line seen in dark surroundings into alignment with the body axis with a standard deviation of under 1°. Supine subjects are slightly less precise

(Templeton 1973).

We can specify the orientation of a test line with respect to each of the frames of reference, as shown in Figure 3. The test line could be a felt rod, a seen line or the body axis. The perceived direction of the test line to each frame of reference and the weight assigned to that information constitute a vector. According to Mittelstaedt (1983, 1986), the perceived orientation of a test object is determined by the sum of the three vectors.

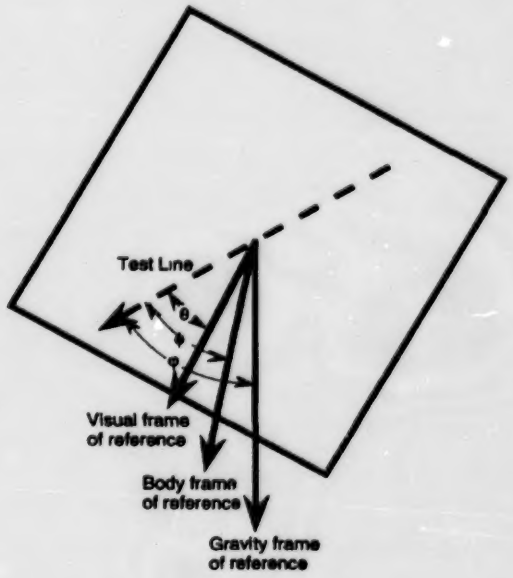

Figure 3. The three frames of reference for perceived orientation of a test line with respect to gravity. The orientation of the test line with respect to the visual, body and gravity frames of reference is θ, ϕ and φ respectively. The perceived orientation of the test line is assumed to be some weighted combination of the registered values of these three angles.

Witkin and Asch pioneered the study of the effects of the visual frame on the perception of the vertical. They found that a luminous square frame in dark surroundings tilted 28° in the frontal plane causes a vertical rod to appear tilted on average 6° in the opposite direction, but with large intersubject variability (Witkin and Asch 1948c; Witkin 1949). This is the well-known rod and frame effect. A frame tilted 28° has also been found to induce a mean illusory tilt of subjects' bodies of 2.8° (Sigman et al. 1978). Nemire and Cohen (1993). found that a grid-lined box inclined 20° about the pitch axis of an erect subject induced about 8° of illusory forward pitch of the self. Howard and Childerson (1994) asked subjects to set a rod to the apparent vertical as they sat erect

in a dot-lined cubic room that could be inclined to any angle about the line of sight. Settings were accurate whenever an axis of symmetry of the room was aligned with the subject's body axis, which occurred at 45° intervals. At intermediate angles the rod was set on average up to 4° in the direction of tilt of the nearest axis of symmetry.

There have been a few reports of displacements of the visual vertical due to viewing a polarized visual scene. Wertheimer (1912) reported that a furnished room seen in a mirror so that it was optically tilted 45° appears gradually to right itself. Asch and Witkin (1948a) repeated the experiment with a mirror that tilted the image of a room 30°. Out of 49 subjects, 32 reported that the room appeared within 2° of vertical and set a rod to apparent vertical accordingly. A few subjects did not experience the illusion and others were unable to make consistent judgments. Other anecdotal reports of a similar kind are described in Howard and Templeton 1966).

Kleint (1936) conducted the first quantitative study of the effects of viewing a tilted furnished room. A small room described as "... decorated with wallpaper, pictures, etc." was inclined up to 40° about the pitch axis of a subject sitting upright. The subject set a rod to apparent vertical in the median plane. For a room inclination of 30°, the mean rod setting of five subjects was 13.2° in the direction of room pitch. Asch and Witkin (1948b). had subjects look into a 4 feet wide by 4 feet deep room tilted 22° about the roll axis. The room had no ceiling but contained a chair, a table and a shelf with a book on it. A rod appeared vertical when tilted about 15° in the same direction as the room. The illusory tilt of the rod increased to about 19° when subjects were tilted 24° with or against the room. Thus, a polarized scene induced larger displacements of the visual vertical than a non-polarized visual frame. Passey (1950) exposed subjects to a room tilted up to 20°. Subjects perceived themselves as upright when they were tilted about 4° in the same direction as the room. But the room contained only two small pictures in the corners.

Several investigators, including Stratton (1897) and Kohler (1953), had subjects wear optical devices that inverted the visual world. It is difficult to decide from their reports whether the visual world came to appear upright, even after wearing the devices for several days, but the field of view was only about 10° (Howard 1982). Morant and Beller (1965) had subjects set a test line to vertical after 15 minutes of sitting in or walking in a building while wearing prisms which rotated the scene by up to 75°. With passive viewing the line appeared displaced about 3°, and after walking it appeared displaced about 8° in the opposite direction to the tilt of the scene. The small effect was probably due to the small field of view through a prism and to the fact that they measured only the aftereffect. Field size has been shown to be an important factor in the generation of illusory tilt. Ebenholtz and Benzschawel (1977) found that a frame tilted 22° induced a mean illusory tilt of a test rod of 7.5° when the stimuli were 1 m away and subtended 56° but no illusory tilt of the rod when the stimuli were 5 m away and subtended 12°. In another experiment, Ebenholtz (1977) found that the crucial factor is the angular subtense of the stimulus rather than distance. Allison et al.

(1999) recorded the percentage of stationary subjects experiencing complete self rotation when viewing our furnished room rotating about the roll axis. When the field of view was unrestricted, 80% of subjects experienced full self rotation but when the field of view was restricted to a diameter of 20°, only 25% of subjects experienced full rotation.

Howard and Childerson (1994) placed erect subjects inside a furnished 7-foot cubic room containing a rich variety of polarized objects, such as furniture, a door and a window with an outside scene. The room also contained objects with extrinsic polarity, such as objects on the floor, on shelves or on the table. The room was tilted up to 120°. Whereas subjects used the nearest axis of symmetry in the dot-lined cubic room as their frame of reference for vertical, they used the nearest surface in the furnished room. Singer *et al.* (1970) obtained a similar difference between an empty and a furnished 4-foot cubic room. Illusory tilt of a rod or of the self in Howard and Childerson's 7-foot furnished room was on average 15° and never exceeded 60°. Thus, for erect subjects, a tilted polarized visual scene is not sufficient to override conflicting otolith and somatosensory signals. Coats and Norfleet (1998) had subjects in underwater scuba suits enter a 12-foot cubic room immersed in water. The room contained a few polarized objects. When the room tilted at 90 or 180° to gravity many subjects became sick when they pitched the head or set a series of clocks. The subjects' perceived orientation of the self to gravity was not reported.

Motion of the visual surroundings can also affect the perceived orientation of the self. Upright subjects exposed to a large textured display rotating about the roll body axis felt as if they were moving continuously in the opposite direction (vection) but, paradoxically, they felt tilted at a mean constant angle of 15° in the opposite direction (Held *et al.* 1975). A textured display moving up or down induces an illusion of self forward or backward pitch respectively (Young *et al.* 1975). Howard *et al.* (1988) obtained similar effects in subjects sitting inside a nine-foot diameter sphere lined with dots and also showed that supine subjects experience illusory yaw tilt when the visual surroundings rotate about the z body axis. The mean angle of illusory self tilt, pitch, or yaw was about 20° and rarely exceeded 90°. A few subjects had the illusion that they were supine and looking up at the axis of rotation of the sphere. This reorientation illusion removes the conflict between vision and the otolith organs because the otolith organs do dot respond to roll motion about a vertical axis (Schöne 1984).

In all these experiments the displays contained no visual information about the direction of gravity so that the effects were due wholly to visual motion. The limited extent of illusory self tilt is due to the restraining influence of proprioception and of inputs from the otolith organs. Patients with bilateral vestibular loss experienced full self rotation (Cheung *et al.* 1989).

The otolith organs provide a less reliable signal when the utricular maculae are not horizontal. Thus, judgments of the visual vertical become more variable when the head is tilted (Graybiel and Clark 1962; Dichgans *et al.* 1974; Schöne and Udo de Haes 1968). For example, Witkin and Asch

(1948b) reported that the mean variable error of setting a luminous to vertical was 1.5° for erect subjects and 16° for recumbent subjects.

In addition, constant errors in judging the vertical occur when the body is tilted. For many people, tilting the head up to about 30° causes a vertical line to appear tilted about 5° in the same direction (E effect), an effect similar in magnitude to the counterrolling of the eyes (de Graaf et al. 1992). Head tilts more than 60° cause a line to appear tilted up to about the same amount in the opposite direction (M effect) (Howard 1982). However, some people show the A effect for small head tilts.

Finally, visually induced tilt illusions are stronger when the body is tilted. Thus, illusory self tilt induced by visual motion is greater when the head is tilted 90° or 180° rather than erect (Young *et al.* 1975). Witkin and Asch (1948a) found the percentage of subjects who perceived an optically tilted room as upright increased from 36% to 59% when they were also tilted. In the presence of a tilted frame, constant errors due head-tilt interact with those due to frame-tilt (Guerraz et al.1998)

When the head is pitched forward about 30° an increase in the gravito-inertial force acting along the z body axis has no effect on the perceived direction of vertical (Schöne 1964; Correia et al. 1968). This suggests that the utricular maculae are inclined back 30° with respect to the z body axis.

Two anecdotal reports suggest that rotation of a polarized scene can completely overcome the restraining effect of non-visual senses to the direction of gravity. In a fairground device built in Los Angeles towards the end of the last century, observers sat in a stationary gondola suspended in a furnished room. The room oscillated sinusoidally with increasing amplitude to simulate the visual effects of sitting in a rocking gondola (Wood, 1895). The people felt that room was stationary and that they and the gondola had rotated about the pitch axis with increasing amplitude. This does not prove that visual factors overcame the restraining influence of inputs from the otolith organs because the axis of room rotation was several feet above the heads of the people in the gondola. If the gondola had actually rotated, the centrifugal force acting on the heads of the observers would have kept the otolith hair cells aligned with the resultant force acting along the body axis. Signals from the semicircular canals that would have arose from rotary acceleration of the head were absent, but this was not sufficient to restrain the visually induced illusion. Kleint (1937) placed people in a furnished room with their heads on the axis of rotation. As the room rotated completely about the roll axis some subjects reported sensations of total self rotation and some reported that they felt a side-to-side oscillation. No quantitative data were presented.

Howard and Childerson (1994) rotated their 7-foot cubic furnished room about the roll axis passing through the head of a seated stationary subject. Sixty percent of adult subjects felt that they were tumbling head-over heels through 360°. In a subsequent experiment with an 8-foot room with a greater number of polarized objects (Figure 4) 80% of erect subjects experienced complete illusory tumbling about the roll body axis (Howard *et al.* 1997; Jenkin, Howard and Hu 1999).

Most subjects also experienced complete tumbling when sitting upright in the room as it rotated about the pitch axis of the head, or when lying supine with the room rotating about the mid body (Howard *et al.* 1997).

The evidence reviewed above suggests that a rotating scene containing polarized objects can overcome conflicting inputs from the otolith and proprioceptive organs and induce a sensation of complete self rotation about the roll or pitch axis in most erect observers. However, the evidence suggests that a stationary scene, even one containing a rich variety of intrinsically and extrinsically polarized objects, cannot induce a sensation of self tilt of more than about 20° in the presence of conflicting otolith/proprioceptive inputs. But in all the above experiments subjects sat upright and the axis of the tilted visual scene was not aligned with the body axis. Before we can draw general conclusions about the power of stationary visual stimuli to overcome conflicting inputs from gravity sense organs we need to conduct experiments with the subject in several postures with respect to gravity and with respect to the visual scene. The experiments reported here were designed for this purpose.

We approached the experiment with three hypotheses.

Hypothesis 1. A reorientation illusion induced by a polarized visual scene at 90° or 180° to gravity is less likely to occur when the subject is erect to gravity rather than inverted, recumbent, supine, or prone. This should be true if the otolith organs provide more reliable information about body orientation when the body is erect rather than tilted 90° or inverted.

Hypothesis 2. A 90° reorientation illusion is more likely to occur than one involving a 180° change in perceived orientation.

Hypothesis 3. A visually induced reorientation illusion is more likely to occur when the subject is aligned with the polarity axis of the visual scene rather than being in another off-vertical orientation. This should be true if a tendency to judge 'down' as being in the direction of the feet reinforces a tendency to judge 'down' in the direction of the visual frame of reference.

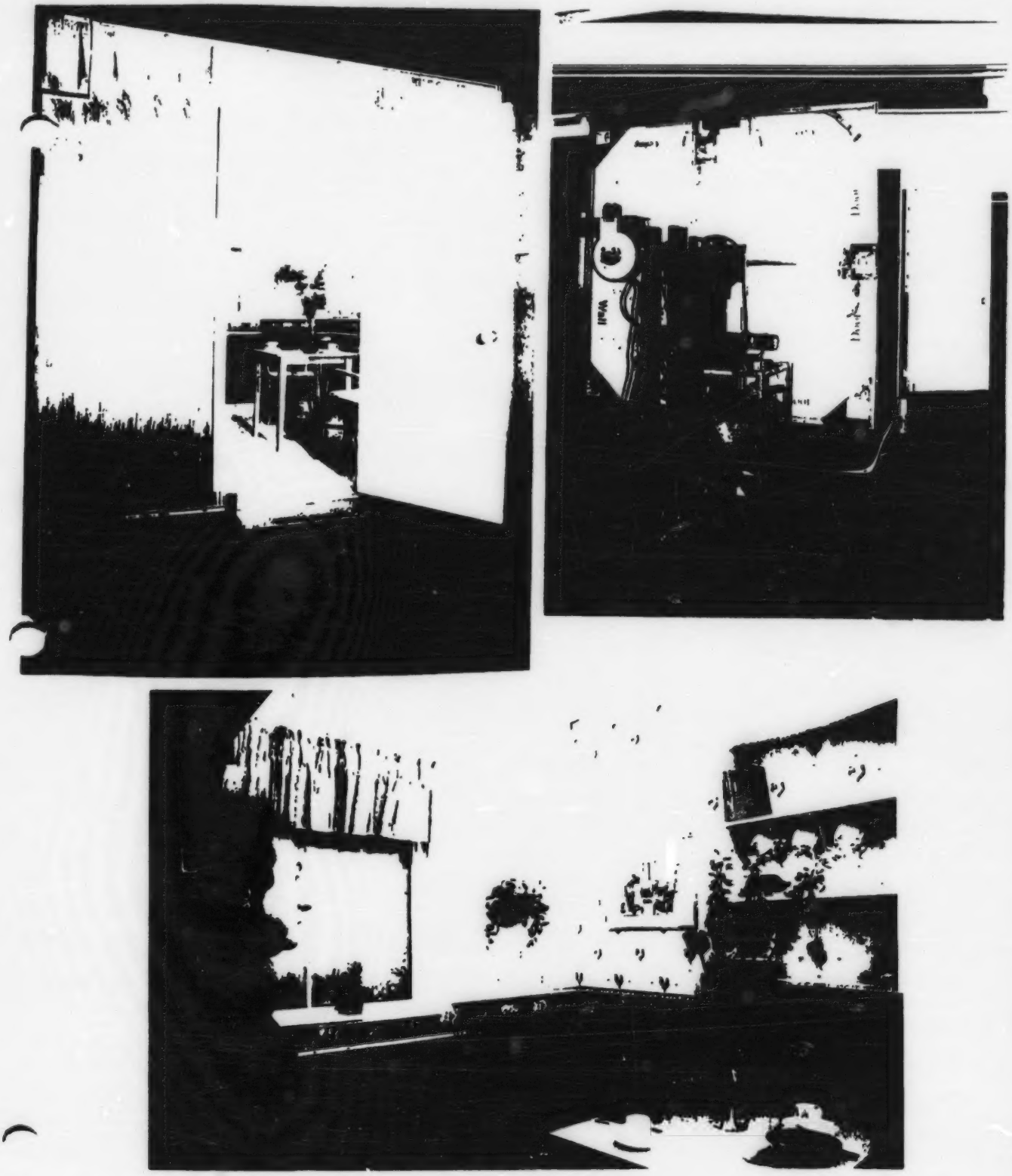

Figure 4. (a) General view of the rotating furnished room. (b) View of the drive mechanism. A computer controlled two servo motors, one rotating the room and the other rotating the chair. (c) View of the wall facing the subject in each of the 18 conditions.

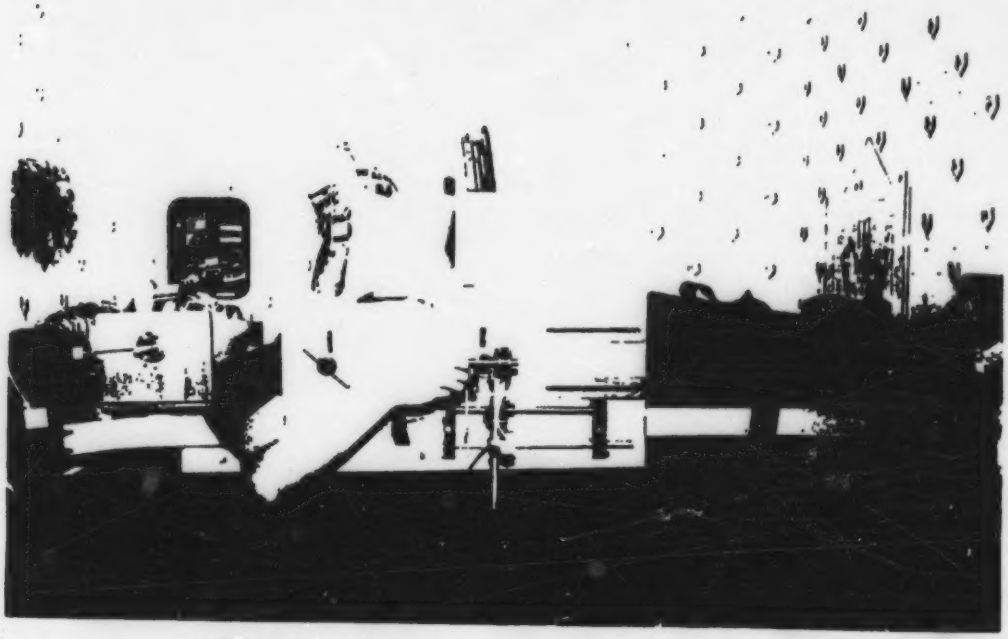

Figure 5. (a) Subject strapped on the bed. (b) Subject strapped in the chair. In each case, the subject can set an unseen tactile rod with one hand and a visible rod with the other.

EXPERIMENT B1

Reorientation Illusions as a Function of Three Frames of Reference

Methods

The basic apparatus in shown in Figure 4a. It consists of an 8-foot cubic room made from a steel frame lined with half-inch foam plastic. The wallpaper contained pictures of animals, the ceiling had a central lamp and the floor was carpeted. One wall contained the door and the other walls had pictures, a bookshelf with objects on the shelves, and a wall clock. Two chairs and a table with cups, basket and other visually polarized objects, as shown in Figure 4c. All objects were firmly attached so that they did not move when the room rotated. Thus the room contained a rich variety of familiar objects with axes of intrinsic visual polarity and objects supported on other objects to provide extrinsic visual polarity.

The subject was supported on a chair or on a horizontal bed. The chair was suspended on the end of a boom protruding through one wall of the room, as shown in Figure 5b. The bed was suspended between the same boom and a bearing set in the opposite wall, as shown in Figure 5a. To reduce tactile sensations, thick foam plastic was placed on the chair or bed and a padded breast plate was strapped against the subject's chest. Straps secured the subject's torso and legs, and padded plates supported the back, top, and sides of the head. The arms were free to move. A tactile rod 19 cm long was placed by the side of the subject in such a position that the subject could not see it. A visual rod 41 cm long with an arrowhead on one end was suspended in full view and within arm's reach in front of the subject. Subjects used a hand to rotate each rod in a plane parallel to the frontal or sagittal plane, depending on the experimental condition.

The room was suspended on bearings, as shown in Figure 4b, so that it could be rotated by a servo motor 360° about its mid-horizontal axis. The chair or bed could be rotated by a second servo motor through 360° about the same horizontal axis as the room. When the chair faced along the axis of rotation of the room the subject could be rotated about the roll axis of the body into upright, left recumbent, right recumbent, or inverted postures. When the chair was orthogonal to the axis of rotation of the room the subject could be rotated about the pitch axis into upright, supine, prone, or inverted postures. When on the bed, the subject could be rotated about the horizontal yaw body axis into supine, prone postures.

A microphone attached to the side of the chair and speakers mounted on a headset allowed the subject to speak to and hear instructions from the experimenter outside the room. Subjects' responses were recorded.

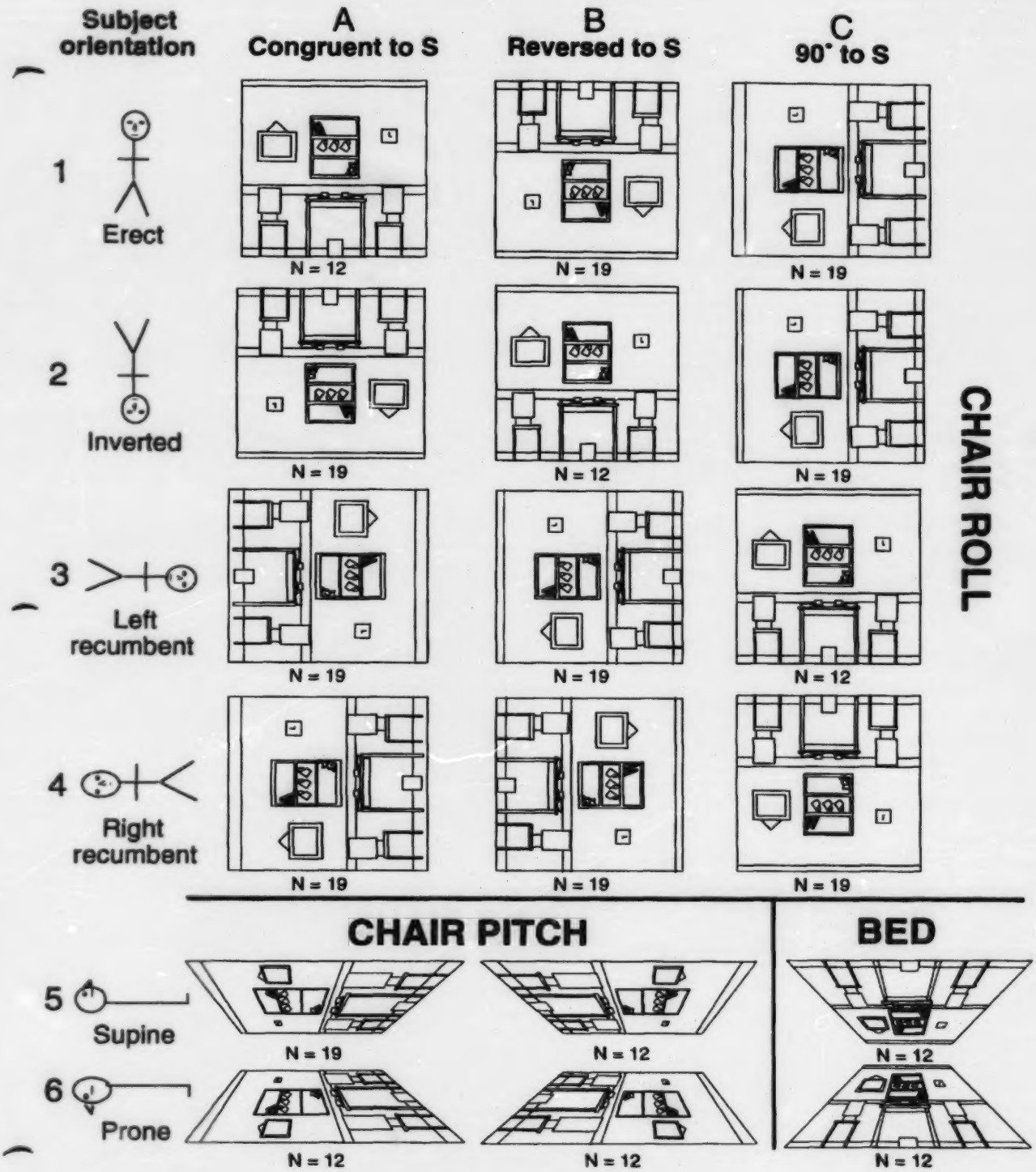

Figure 6. The 18 conditions used in Experiment B1. For each of six orientations of the subject the room was vertical, inverted or at 90°.

Stimulus Conditions

On a 90° period, a human body axis can be oriented six ways to gravity—upright, inverted, supine, prone, and left and right recumbent. A room can also be oriented six ways (each of the six surfaces can be the bottom horizontal surface). This gives 36 relative orientations of subject and room. We ignored six conditions that involved a trivial change of symmetry, for example, whether the room tilted clockwise or counter-clockwise 90° to subjects. We also ignored conditions in which the subject faced the ceiling or floor because we wished to keep the contents of the visual display constant across conditions. This ensured that any effects of changing the orientation of the room were due to orientation and not to any other change in the visual display. This reduced the number of conditions to 18. The wall that faced the subject in the roll posture was decorated in the same way as that which faced the subject in the pitch posture. Since the two walls were not actually the same, we moved the wall decorations and furniture so that they appeared the same. The 18 conditions are shown in Figure 6. The left hand column shows the six body orientations. The other columns show the orientations of the room surface facing the subjects. In column A, subjects faced a "congruent wall" with a polarity axis that was congruent with the body axis. In column B, subjects faced a "reversed wall" that was inverted with respect to the body. In column C, subjects faced a "90° tilted wall" that was rotated 90° relative to the body.

Subjects

In a preliminary test, each of 30 seated subjects was rotated slowly into a supine posture while the room rotated completely several times, coming to rest with a horizontal wall above the subject. After one minute, the subject reported the perceived direction of gravity and the orientation of the room and self to gravity. Twelve of the subjects reported they were upright or nearly upright in an upright room. These 12 subjects (7 female, 5 male, ages 19 to 70) were used in the main experiment. Since the purpose of the main experiment was to determine how the incidence of reorientation illusions varies as a function of body and room orientation, there was no point in testing subjects who did not experience reorientation illusions. An additional seven subjects (2 female and 5 male, ages 20 to 37) were pre-selected and tested in some of the conditions of the main experiment.

No subject had any known ocular, ocular-motor or vestibular pathology. Subjects were paid. The use of human subjects was approved by the York University Human Participants Review Sub-Committee.

Procedure

The experiment consisted of three sessions. In session one, the chair rotated about the pitch axis of the body. In session two, the chair rotated about the roll axis. In session three, the bed rotated about the yaw mid-body axis. The order of three sessions was counter balanced across subjects.

In each session, the subject was securely strapped into the chair or bed. The room and the subject, with eyes open, were rotated together at 3°/s about a horizontal axis to the test position. The subject was then asked to wait for about 1 minute and then perform the following tasks.

Settings of a tactile rod, a visual rod, and verbal responses were used to record the perceived direction of down. A tactile rod 19 cm long was placed by the side of the subject in such a position that the subject could not see it. A visual rod 41 cm long with an arrowhead on one end was suspended in full view and within arm's reach in front of the subject. Subjects used a hand to rotate each rod in a plane parallel to the frontal or sagittal plane, depending on the experimental condition. Subjects set each rod to the apparent vertical, with the long end of the tactile rod and the arrowhead of the visual rod pointing down. The angular settings of the rods were indicated by voltages from potentiometers. The subject was then asked to judge the orientation of the room and of the self to gravity and to state which surface of the room would a ball fall to if released. If the verbal responses about the orientation of the room and the self were in conflict, further questions were asked to make sure the subject understood the questions. Finally, the subject was asked to close the eyes, set the unseen rod to "down" and report body orientation to gravity.

Results

A judgment of 'down', as indicated by rod settings and verbal estimates, was deemed to conform to a given frame of reference if it was within 15° of 'down' defined by that frame of reference. A subject who was confused about the orientation of the room or of the self or whose rod settings and verbal responses were in conflict, was recorded as confused. Responses made when the subject and room were upright to gravity were not included in the analysis.

The results are shown in Table 6. Under each panel is listed the percentage of subjects for whom the perceived direction of 'down':

1. conformed to gravity.
2. conformed to the visual frame.
3. conformed to the body axis (direction of the feet)
4. was more than 15° from alignment with any frame of reference.
5. was confused or contradictory.

A subject was scored as having a reorientation illusion if the self and rods were perceived as tilted 90° or 180° (±15°) with respect to their true orientation to gravity. There are three types of reorientation illusion.

(1) A pure visually induced reorientation illusion in which 'down' conforms to the visual frame but not to gravity or the body axis.

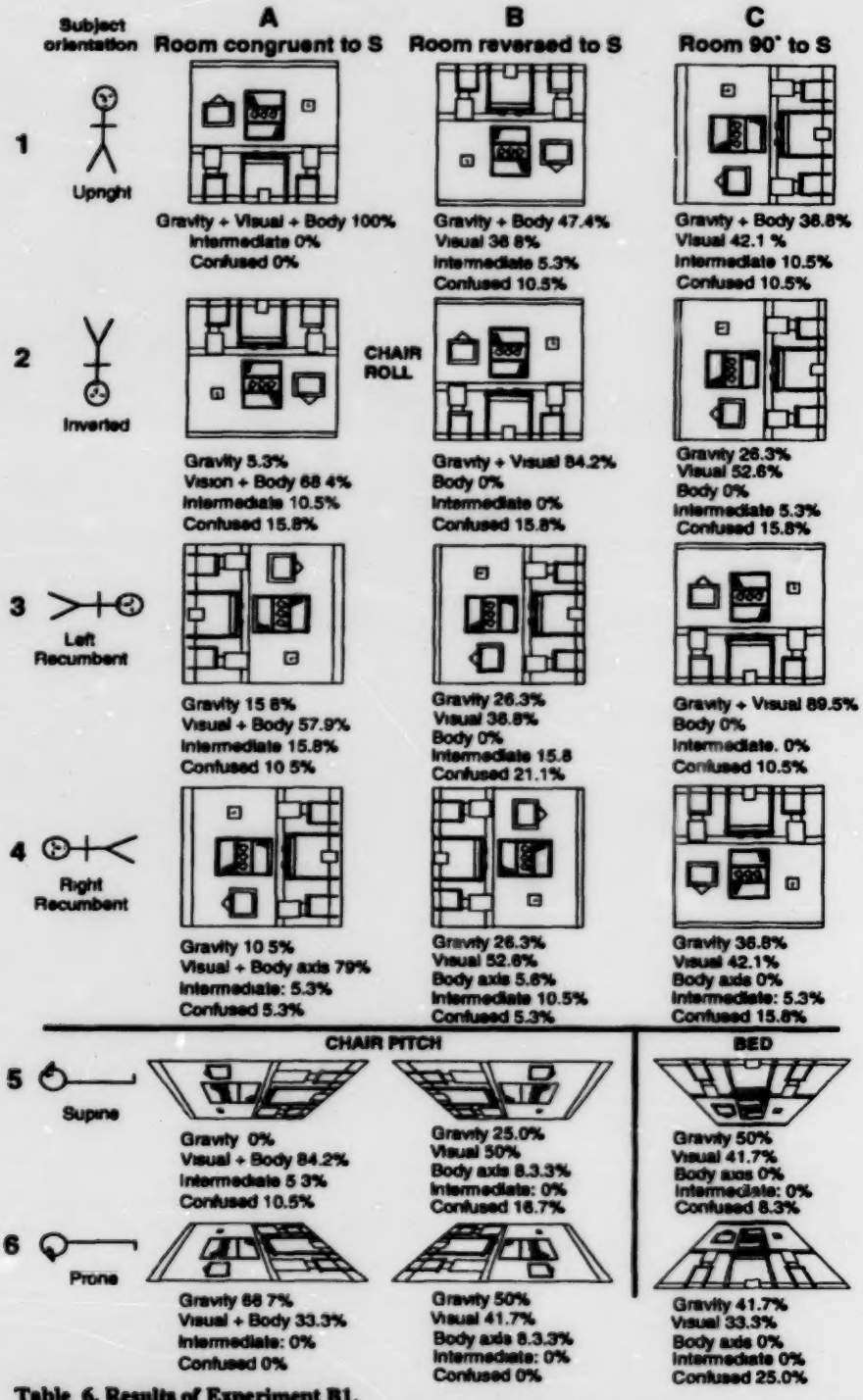

Table 6. Results of Experiment B1.
The percentage of subjects who judged 'down' in line with gravity, the visual frame, the body axis, and at an intermediate angle, and the percentage who gave confusied responses.
Each panel shows the orientation of the facing wall of the room to gravity.

(2) A mixed reorientation illusion in which 'down' conforms to both the visual frame and the body axis but not to gravity.

(3) A pure body-axis (idiotropic) reorientation illusion in which 'down' conforms to the body axis but not to gravity or the visual frame.

Perceived 'down' in line with gravity

Table 7 shows the percentage of trials in which perceived 'down' was in line with gravity.

Down' aligned with gravity when:	Conditions	No. of trials	Percentage
Body upright	B1, C1	16 out of 38	42.1%
Room upright	B2, C3	33 out of 38	86.8%
Room and body tilted or inverted congruently	Column A	14 out of 88	15.9%
Room and body tilted or inverted non-congruently	B3 to 6, C1, 2, 4, to 6	42 out of 124	33.9%

Table 7. Percentage of trials in which perceived 'down' was in line with gravity.

The results can be summarized as follows. Perceived 'down' was in line with gravity (correct) when the room was erect, although a few subjects gave inconsistent responses. Fewer than half the responses were correct when the body was erect but the room was tilted or inverted. Only a few responses were correct when both the body and visual frame were tilted or inverted together. About a third of responses were correct when the body and room were tilted in different ways. The main conclusion is that the perception of self to gravity is maintained when the visual frame is erect but is severely disrupted in a large proportion of subjects when the visual fame is tilted 90° or 180°. The disruption is more severe when the subject is also tilted or inverted. This supports Hypothesis 1.Disruption is particularly severe when the body and visual frame are tilted or inverted in the same way. This supports Hypothesis 3.

Perceived 'down' in line with the body axis

Table 8 shows the percentage of trials in which perceived 'down' was set in line with gravity.

'Down' aligned with the body when:	Conditions	No. of trials	Percentage
Body upright	B1, C1	16 out of 38	42.1%
Room and body tilted or inverted congruently	Column A	59 out of 88	67%
Room upright	B2, C3	None	0%
Room and body tilted or inverted non-congruently	B3 to 6, C1, 2, 4, to 6	3 out of 124	2.4%

Table 8. Percentage of trials in which perceived 'down' was in line with the body axis.

The results can be summarized as follows. In many cases 'down' was aligned with the body axis when the body was erect and the room was tilted or inverted. Most subjects aligned 'down' with

the body when the body and frame were tilted or rotated in the same way (congruently). However, there were virtually no pure idiotropic reorientation illusions. Thus, no subject judged 'down' to be in the direction of the feet when the body was tilted or inverted and the room was upright. Thus, the visual and gravity frames of reference acting together override any tendency of subjects to use the idiotropic vector. Also, 'down' was judged to be in the direction of the feet in only three trials out of 124 when the body was not erect and not aligned with a tilted visual frame. Thus, in almost all cases in which 'down' was set in line with the body axis it was also in line with either gravity or the visual frame.

Perceived 'down' in line with the visual frame

Table 9 shows the percentage of trials in which perceived 'down' was in line with the visual frame.

'Down' aligned with visual frame when:	Conditions	Trials	Percentage
Room upright	B2, C3	33 out of 38	86.8%
Room and body tilted or inverted congruently	Column A	59 out of 88	67%
Body upright	B1, C1	15 out of 38	39.5%
Room and body tilted or inverted non-congruently	B3 to 6, C1, 2, 4, to 6	55 out of 124	44.4%

Table 9. Percentage of trials in which perceived 'down' was in line with the visual frame.

The results can be summarized as follows. Almost all judgments of 'down' were correct when the visual frame was upright, whatever the orientation of the subject. Most judgments were in line with the visual frame when the visual frame and body were tilted or inverted congruently. This again supports hypothesis 3. Fewer responses were in line with a tilted visual frame when the body was erect (Hypothesis 1) or not aligned with the visual frame (Hypothesis 3). The statistical significance of these differences is discussed below.

Visually evoked reorientation illusions

There were virtually no pure idiotropic reorientation illusions. Almost all reorientation illusions were either purely visually induced or conformed to both the visual frame and to the body axis. For simplicity, we will refer to all these reorientation illusions as visually induced. We devote further analysis to factors that influence the incidence of visually evoked reorientation illusions.

The perceived changes in body orientation relative to gravity that would occur if the subject judged the floor of the room to be down are shown in Table 10. Table 10 also shows the percentage of trials in which a visually evoked reorientation illusion occurred for each of the 18 conditions of the experiment.

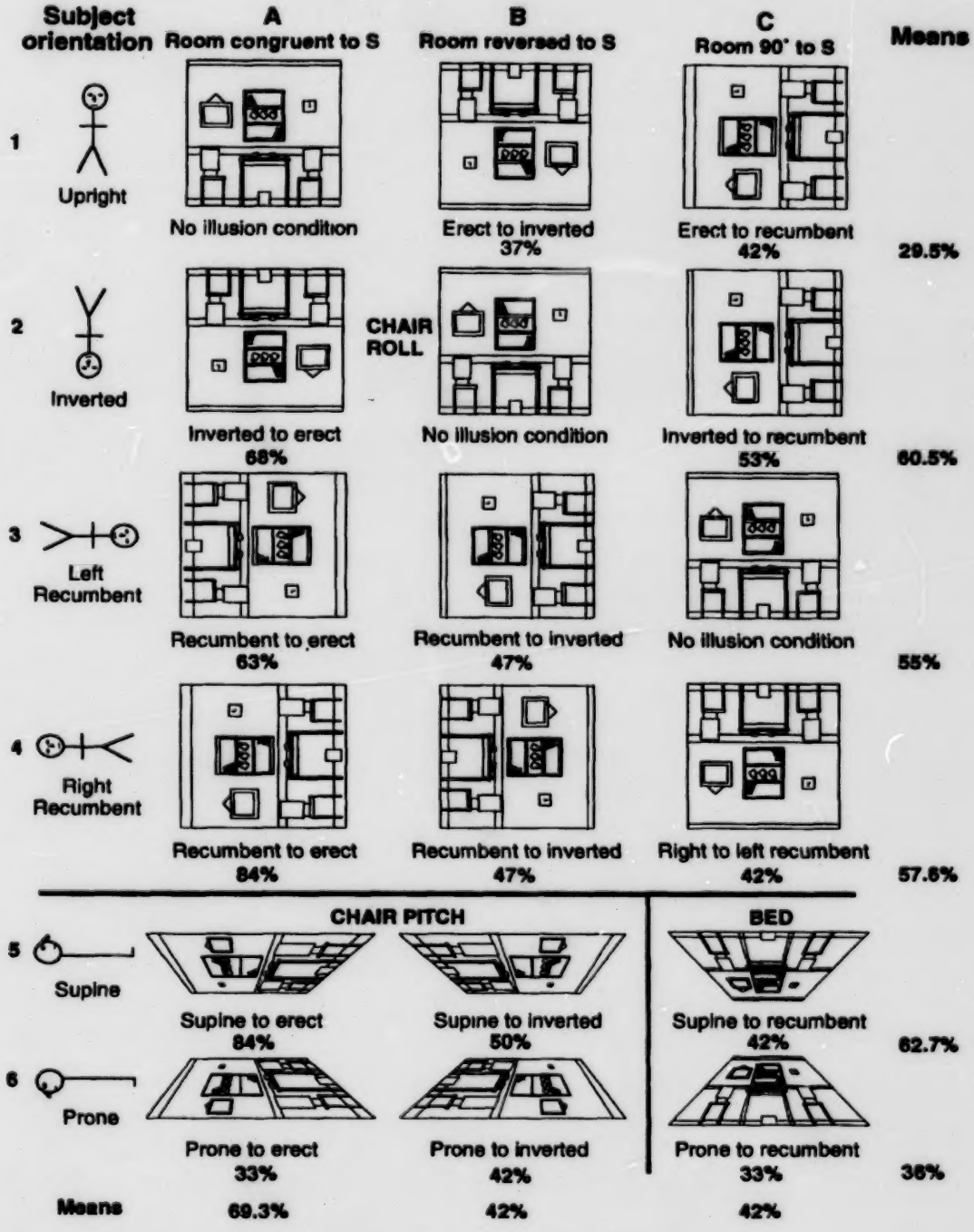

Table 10. Percentage of subjects experiencing a visually induced reorientation illusion. Each panel shows the orientation of the facing wall of the room to gravity.

We first consider the influence of the orientation of the room to gravity on the incidence of visually evoked reorientation illusions. Table 11 shows the percentage of trials in which visually evoked reorientation illusions occurred for each orientation of the room to gravity. Visually evoked reorientation illusions could not occur when the room was upright (conditions A1, B2 and C3). We have already noted that reorientation illusions induced by displacement of the body axis were also absent when the room was upright. Perceived 'down' was aligned with the room axis in 56% of cases when the room was tilted 90°, in 50.6% of cases when the room was pitched 90°, and in a 47.2% of cases when the room was inverted. These differences were not significant. Overall, when the room was not erect, 'down' was aligned with gravity in 29.6% of cases and with the room axis in 51.6% of cases. Thus, for this pre-selected group of subjects, the perception of 'down' was more strongly determined by the visual frame of reference than by the gravity frame of reference when the two frames of reference were in conflict.

Orientation of room gravity			
Tilted 90°	Pitched 90°	Inverted	Not erect
56%	50.6%	47.2%	51.6%

Table 11. Percentage of subjects experiencing a visually evoked reorientation illusion as a function of the orientation of the room to gravity.

We next consider the influence of the orientation of the body to gravity on the incidence of visually evoked reorientation illusions. Effects produced by different orientations of the body to gravity are revealed by the row means of Table 10. There was a significant overall difference between row means [$\chi^2(8, N=246) = 18.79$, $p = 0.0016$]. When the body was erect (row 1) only 29.5% of subjects experienced a reorientation illusion, compared with 53.7% when the body was not erect (rows 2 to 6). This confirms Hypothesis 1. The prone posture induced fewer illusions than recumbent postures [$\chi^2(2, N=127) = 17.65$, $p < 0.001$], the supine posture [$\chi^2(2, N=79) = 9.06$, $p = 0.011$], or the inverted posture [$\chi^2(2, N=74) = 14.6$, $p < 0.001$]. Thus, reorientation illusions occurred in only 36% of trials when subjects were prone compared with 57.3% of trials when subjects were inverted, recumbent or supine. There were no significant differences between supine, recumbent and inverted body orientations. We had predicted in Hypothesis 2 that a 90° reorientation illusion is more likely to occur than one involving a 180° change in perceived orientation. The results do not support this prediction.

The influence of body posture on the incidence of visually induced reorientation illusions can be explained by sensory conflict theory. When sources of information are in conflict, they produce

a compromise percept. For example, when an erect person views a 90° rotated room, visual information indicates that the body is tilted in the same direction while the gravity sense organs indicate that the body is erect. We have already mentioned that the utricles are probably most sensitive when the hair cells are vertical, which occurs when the head is pitched forward about 25°. This would explain why reorientation illusions occur less frequently when the body is erect. Another factor that could account for the lower incidence of illusions in the erect posture is that the idiotropic and gravity frames of reference are congruent when the subject is erect.

The fact that the utricles are most sensitive when the head is pitched forward 25° could also explain why illusions occur more frequency in the supine posture than in the prone posture. Prone subjects are closer to the orientation of greatest utricle sensitivity than are supine subjects. Young et al. (1975) found that illusory body tilt induced by a tilted visual scene increased for head rolled 90° to the side or inverted, and decreased for the head pitched forward 25°.

Effects of congruence of the visual frame and the body axis on the incidence of visually induced reorientation illusions

The influence of the relationship between body axis and room axis on the incidence of visually induced reorientation illusions is revealed by comparing the column means of Table 10.

When the body axis and room axis were congruent (column A), a reorientation illusion occurred in 69.3% of cases. Under these conditions, all body orientations except the prone orientation produced a high incidence of illusions. When the body and room axes were relatively reversed or orthogonal an illusion occurred in only 42% of cases. Chi-square tests revealed a significant difference in the incidence of illusions between columns A and B [$\chi^2(2, N = 169) = 10.80$, $p = 0.005$] and between columns A and C [$\chi^2(2, N = 167) = 13.47$, $p = 0.001$]. There was no difference between columns B and C. Thus, reorientation illusions occurred more frequently when the body axis was congruent with the room axis than when the two axes were inverted or orthogonal. Thus, Hypothesis 3 is confirmed.

Individual differences

We found large individual differences [$\chi^2(36, N=428) = 129.72$, $p < 0.000$] even though subjects were selected because they experienced a partial or full levitation illusion. Some subjects experienced a reorientation illusion on almost every trial, while some experienced an illusion on only certain trials. Large individual differences were also found in previous studies of tilt illusions (Within and Asch 1948b). We will see in Experiment B2 that older people are more likely to experience reorientation illusions than younger people.

Most subjects gave consistent answers about the perceived orientation of the room, rods, and body. However, some subjects' gave conflicting responses or were unable to answer questions,

even when we asked a given question in several different ways. We must conclude that such subjects were totally confused about their orientation.

EXPERIMENT B2

Visually Induced Reorientation Illusions as a Function of Age

Introduction

In Experiment 1 we reported a new class of reorientation illusions in which the restraining influence of non-visual stimuli is completely overcome by stationary highly polarized visual displays. In one of these illusions a subject is placed in a supine posture inside a furnished room tilted 90° to gravity so that the normally vertical wall is horizontal and above the subject. Many subjects feel that they are upright in an upright room. They report that the arms feel weightless when extended out from the supine body and that an object hanging from the wall above seems to be suspended in space in front of them. We called this the levitation illusion because subjects who had experienced weightlessness in parabolic flight or in Space Lab reported that the sensations resemble those occurring in microgravity conditions.

In previous experiments from this laboratory about 80% of subjects of all ages experienced a dynamic reorientation illusion of complete self rotation when exposed to a furnished room rotating about a horizontal axis (Howard and Hu 1990). We expected that the same would be true of static reorientation illusions. However, we soon found that older subjects were more likely to experience the levitation illusion than younger subjects. In Experiment B3 we measured the incidence of illusory self tumbling induced by rotation of a furnished room and the incidence of the levitation illusion induced by a stationary room tilted 90° in subjects ranging in age from 9 to 78 years.

Methods

We tested 24 subjects in each of four age groups: children (mean age 10 years), young adults (mean age 26 years), older adults (mean age 41 years) and seniors (mean age 72 years). Each subject was securely strapped into a well padded chair in the centre of an 8-foot cubic room filled with visually polarized objects (see Figure 4). The subject and/or the room could be rotated about a common horizontal axis running through the centre of the room. Head phones and microphones allowed two-way communication between subject and experimenter, which was recorded on a tape recorder. Subjects were tested in each of the following six conditions.

Condition 1. Movement to supine position

The subject was secured in the chair facing the door wall of the room. Subject and room were rotated back 90° about the subject's pitch axis until the subject was supine, looking up at the door wall (see Figure 7). If both the self and room appeared within about 15° of their true orientation the response was categorized as veridical. If the both the self and room were perceived within about 15°

of vertical the response was categorized as a reorientation illusion. The subject was then asked to raise his or her arms at shoulder height and report any sensations. Finally, the subject was asked; "What surface of the room would a dropped ball hit?" "If you undid the straps could you step off the chair onto the carpeted floor?"

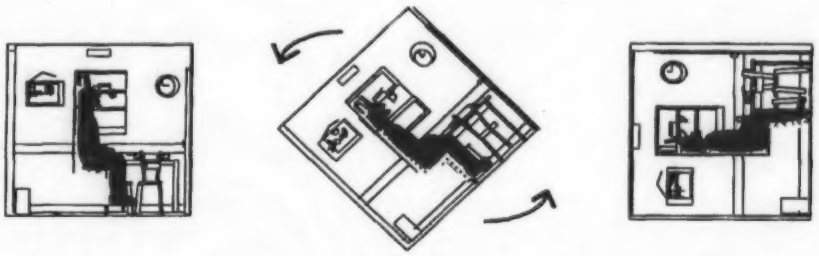

Figure 7. Room and subject were slowly rotated back 90° at 30°/s until the subject was supine and the room was tilted 90° so that the subject facedthe same wall as when he was erect.

Condition 2. Tumbling vection

The room was rotated twice at 30°/s about the pitch body axis of the stationary supine subject. The subject described the perceived motion of the room and of the self. Visually induced illusory motion of the self is known as vection. Subjects reporting partial vection (rotation of both self and room) or full vection (rotation of only the self) were asked how far they felt they had rotated with respect to gravity. Responses were categorized as illusory self pitch if subjects reported that they

became inclined only to a certain angle on each rotation of the room. Note that subjects can experience an illusion of continuous self motion coupled with a feeling that the body is tilted only to a limited extent (Held et al. 1975; Howard et al. 1988). Responses were categorized as a dynamic reorientation illusion if subjects felt they had rotated through 360° in pitch.

Condition 3. Prone illusion

After the room completed its two rotations about the stationary supine subject it was brought to rest with the carpeted floor above the subject (Figure 8). Subjects experiencing a reorientation illusion felt they were suspended in a prone posture looking "down" at the carpeted floor. Subjects were asked the same questions as in Condition 1.

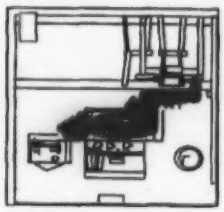

Figure 8. The subject oriented with the floor of the room above.

Condition 4. Control condition—returning room to vertical

The room was rotated into the upright position, with the subject remaining supine. After the room was upright subjects were asked the same questions as in Condition 1.

Condition 5. The levitation illusion again

The room was slowly rotated 90° from upright until the supine subject was again looking up at the door wall. Subjects were then asked the same questions as in Condition 1.

Condition 6. Return to vertical with eyes closed

The subject was asked to close her or his eyes while the room was rotated upright to gravity. With eyes still closed the subject was brought upright from the supine position at 3°/s and asked to indicate when the body felt uprightThe angle at which the subject felt upright was recorded.

Results.

Approximately 90% of all supine subjects of all ages reported an illusion of self pitch through 360° while the room rotated around them (Condition 2). They reported that the room was stationary and they were moving—a sensation similar to doing a somersault. The remaining subjects described a sensation of alternating self pitch. As the room rotated from vertical it

appeared to remain vertical and subjects experienced increasing self pitch. As the room reached a certain angle, usually in the neighbourhood of its being inverted, the subjects suddenly felt upright again and the room appeared tilted from vertical.

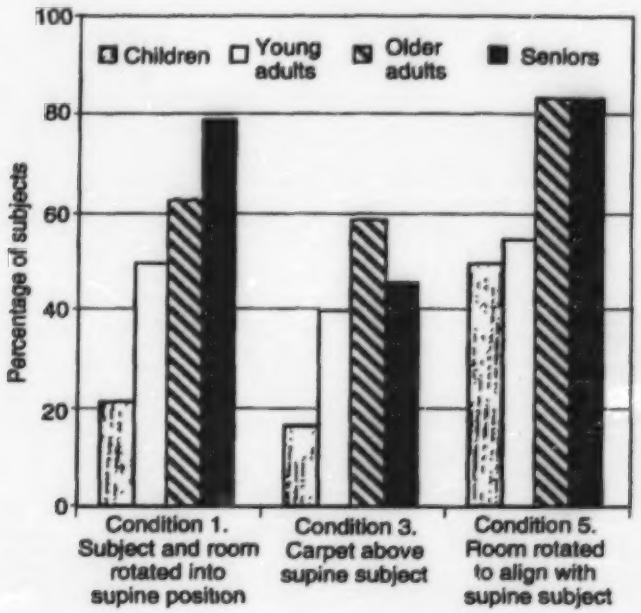

Figure 9. The percentage of subjects experiencing each of three types of reorientation illusion as a function of age. There were 24 subjects in each group.

Figure 9 shows that when the room and subject were rotated together through 90° (Condition 1) the percentage of subjects experiencing the levitation illusion increased across age groups [χ^2 (3, N=96) = 17.86, p = .001]. A less pronounced age trend in the incidence of a reorientation illusion was observed in Condition 3, when supine subjects viewed the floor of the room [χ^2 (3, N=96) = 8.93, p = .03]. A less pronounced age trend was also evident in Condition 5, when the door wall was rotated into alignment with the supine subject [χ^2 (4, N=96) = 10.815, p = .013]. The results of Condition 4 confirmed that all subjects correctly reported that they were supine when the room was gravitationally upright. Seniors had the greatest variability in judging when they were upright in the dark (Condition 6), as shown in Table 12.

Age group	Deviation from vertical	Standard error
Children	14.7°	1.69
Adults	6.5°	1.55
Seniors	29.4°	4.12

Table 12. Mean deviations and constant errors of restoring the body to vertical in the dark in three age groups.

Conclusions

A rotating richly polarized visual environment induces a strong dynamic reorientation illusion in subjects of all ages. This is probably because people of all ages use visual motion to control body posture. Visually induced body sway of seated infants increases from the age of 5 months (Bertenthal and Bai 1989; Sundermier and Woollacott 1998). Infants who have just learned to stand stagger or fall when standing in a striped room that is moved forward and backward (Lee and Aronson 1974) or from side to side (Butterworth and Hicks 1977; Borger et al. 1999). After the age of 3 years the magnitude of visually induced sway declines to its adult level but increases again in elderly people (Foster et al. 1996). Signals arising from visual motion feed into the vestibular nuclei and from there into brain stem centres controlling eye movements and postural responses (Howard 1986). This is a very primitive system that matures early and requires little cortical control or learning.

The increase in the incidence of the levitation illusion with age could be due to; (a) increased experience with or increased reliance on polarized environments and/or (b) loss of vestibular sensitivity.

Concerning the first factor, the levitation illusion is induced only by learned static cues of visual up and down arising from the intrinsic visual polarity of familiar objects in the room or the extrinsic polarity of objects. There is no visual motion and the visual frame (edges and surfaces of the room) remains aligned with the body axis and with gravity. The recognition of the polarity axis of a familiar object must be learned and must therefore rely on cortical rather than subcortical processes. Young children are indifferent to the orientation of pictures in a book and confuse letter orientations (Howard 1982). Also, children must presumably learn about extrinsic polarity arising from how objects are supported, but it has been shown that five-month-old infants are able to distinguish between a supported object and one suspended without support (Needham and Baillargeon 1993).

There is an abundance of evidence of loss of vestibular sensitivity with age. The human vestibular organs lose hair cells and nerve fibres at a rate of about 5% per decade between the ages of 40 and 90 years (Rosenhall 1973; Bergström 1973). With increasing age, macular cilia tend to become disarranged and fused (Rosenhall and Rubin 1975). There is a also an age-related loss of neurones in the vestibular nuclei of the brain stem (Lopez et al. 1997). Older adults show greater postural instability than young adults, whether or not the eyes are open (Perrin et al. 1997; Matheson et al. 1999). Also, the postural stability of older people becomes increasingly affected by motion of the visual surroundings and/or of the platform upon which they stand (Peterka and Black 1990; Teasdale et al. 1991; Whipple et al. 1993). It thus seems that older people have reduced vestibular/proprioceptive sensitivity and increased difficulty integrating visual and vestibular/proprioceptive information. The results from Condition 6 demonstrate that our older

subjects showed greater variability than younger subjects in setting themselves to the vertical in the dark. We suggest that as people lose vestibular sensitivity they come to rely more on visual information, especially that provided by visual polarity.

There were fewer reorientation illusions in all age groups for supine subjects looking up at the carpeted floor of the room. This is probably because the floor contained fewer polarized objects than the wall. Also, the reorientation illusion involved a 180° change in perceived body orientation rather then the 90° change in the levitation illusion.

There was a increase in the incidence of reorientation illusions in the three younger age groups when the room was rotated from vertical into alignment with the supine subject (Condition 5) compared with when both subject and room were rotated together (Condition 1). As the room rotated relative to the stationary subject, almost all subjects of all ages experienced a dynamic reorientation illusion in which they perceived themselves as returning to an erect posture inside a stationary room. They were thus primed by the dynamic reorientation illusion into believing that the room and self were vertical when the room came to rest with the wall surface above them.

There seem to have been no studies on postural stability at different ages as a function of the static tilt of the visual surroundings, but the results of our experiments suggest that the postural stability of older people would be more affected by tilt of a polarized visual scene than that of younger people. Old people in a stairwell lacking polarized visual objects should be particularly unstable because the inclined stairs provide a misleading visual frame of reference. The provision of polarized stimuli, such as pictures, should help.

We tested nine astronauts between the ages of 30 and 40 and found that four of them experienced a levitation illusion in our room. We predict that astronauts will suffer fewer inversion illusions if there were pictures of familiar polarized on the walls of the space habitat. Space modules such as Space Lab and the Mir Space Station were practically devoid of polarized objects. The interior of Space Station is also devoid of visual features that astronauts could use to maintain a stable sense of self orientation.

General conclusions from Part B

In Experiment B1 we revealed a set of novel static reorientation illusions experienced by subjects in supine, prone, recumbent or inverted postures inside a richly polarized room tilted 90° or 180° to gravity. We define a static reorientation illusion as occurring in a stationary observer in stationary visual surroundings when the perceived direction of 'down' is 90° or 180° to the true direction of gravity.

We are not aware of any previous experiments that have investigated 90° or 180° reorientation illusions in normal people on Earth. In the static reorientation illusions that we have described, the subject and a room with a rich variety of polarized objects are at 90° or 180° to gravity so that the surfaces and edges of the room (the visual frame) are not tilted to gravity or to the body axis of the subject. If the room were totally empty, 0°, 90° and 180° room orientations would be indistinguishable. Our reorientation illusions are therefore not related to tilt contrast nor to the visual frame effects studied by Witkin and others. The illusions arise because subjects judge the direction of gravity in terms of the frame of reference provided by the intrinsic or extrinsic polarity axes of objects in the room and/or the body axis. The frame of reference provided by the gravity sense organs is ignored.

We first consider whether each of the three frames of reference can dominate judgments of self orientation to gravity when both the other frames indicate a different direction of gravity.

Gravity frame of reference When the body was erect and the room was tilted or inverted, perceived 'down' was aligned with gravity about as often as with the visual frame. When both the room and body were not erect (conditions in rows 2 to 6), 'down' responses were more often determined by the visual frame than by gravity.

Although the visual frame was dominant over gravity when subjects were inverted, recumbent or supine, gravity was dominant when subjects were prone (conditions in row 6). This could be because the prone body is closer to the posture of maximum utricular sensitivity than the supine body. Another factor could be that tactile/proprioceptive information to the orientation of the body was stronger for subjects hanging face down in the chair or bed than for subjects lying on the back.

Visual frame of reference When the visual frame was upright to gravity, reorientation illusions did not occur, although a few subjects were confused about their orientation (conditions A1, B2, and C3). The high incidence of visual-frame responses in the subjects tested in Experiment B1 cannot be generalized to a broader population because the subjects were pre-selected for their susceptibility to visually induced reorientation illusions. The experiment was designed to explore the factors that

contribute to reorientation illusions in a group of subjects who were pre-selected for susceptibility to visually induced reorientation illusions.

The mean incidence of visually induced reorientation illusions did not differ significantly between 90° pitch, 90° roll, and 180° inversion of the room.

Body-axis frame of reference Only two subjects reported 'down' to be in the direction of the feet when the other two frames of reference indicated other directions (conditions B4, B5, and B6). The same two subjects continued to perceive the feet as 'down' after they closed their eyes while recumbent, supine, or prone. Thus, very few reorientation illusions were due to the perception of the feet as 'down'. In the weightless conditions of space, astronauts often perceive 'down' as in the direction of the feet. But, in these conditions, the gravity frame of reference is absent and the visual frame is impoverished because the interiors of space vehicles contain very few polarized objects. We found that our room did not induce reorientation illusions when it was configured as a full-scale replica of space station. There are anecdotal reports that sight of another astronaut in a reversed orientation can destroy the impression that the feet are 'down'. Thus, it seems that ones body axis is the dominant frame of reference for vertical only when gravity is absent and the visual frame is weakened.

Interactions between body-axis and visual frame There was a significantly higher incidence of reorientation illusions when the body axis was congruent with the visual axis (column A) than when the body axis was inverted (column B) or orthogonal to the visual frame (column C).

Neurological patients may experience episodes in which the visual surroundings suddenly appear tilted through 90 or 180° (Steiner et al. 1987; Tiliket et al. 1996). In several cases, patients feel as if their bodies are dangling in space. The symptoms are usually accompanied by nausea and dizziness. The condition is due to disturbance of central connections of inputs from the otolith organs, arising from vertebral-basilar ischemia or lesions in the parieto-occipital or vestibulo-cerebellar systems (Ropper, 1983).

Aircraft pilots can experience reorientation illusions in banking and roll manoeuvres. These illusions could be influenced by each of the three frames of reference that I have described—the visual frame, the idiotropic frame, and gravity. Our results suggest that the visual frame of reference provided by the interior of the aircraft is the dominant factor. We have shown that about 50% of adults accept a strong visual frame of reference and ignore conflicting information from the gravity sense organs (otolith and tactile-proprioceptive sense organs). Our results suggest that the idiotropic frame of reference (the tendency to perceive the feet as 'down') plays only a minor role in reorientation illusions. We have shown that the idiotropic frame of reference is overwhelmed by

the visual frame of reference when the two frames of reference are in conflict. Our results suggest that reorientation illusions are more likely to occur if a pilot in a roll manoeuvre keeps his head and torso aligned with the aircraft cabin rather than aligned with gravity. When the head is aligned with the cabin, the idiotropic and visual frames of reference are congruent and are more likely to dominate contradictory information coming from the gravity sense organs. When the head tilts in the opposite direction to the tilt of the aircraft the idiotropic and gravity frames of reference are congruent and are more likely to dominate over contradictory visual information.

Spatial disorientation in aircraft pilots is classified into three types. In Type 1 the pilot is not aware of being disoriented. In Type II the pilot is aware of the sensory conflict and in Type III the pilot is aware of being disoriented but is overwhelmed by the conflicting information. We found evidence of a similar classification of responses in our subjects. About 50% of our adult subjects maintained a correct orientation to gravity when they were supine observing a 90° rotated visual scene. Most of the other young adults were dominated by the tilted visual frame of reference to the extent that they ignored conflicting information from the gravity sense organs. Some of these subjects were nevertheless aware that they were supine if they concentrated on pressure sensations on their back. In spite of this awareness they perceived themselves as upright in an upright room. There was thus a dissociation between what they consciously concluded from pressure sensations and the perception of vertical. Like pilots who are aware of the nature of conflicting sensory information, these subject could make allowance for the illusion of being disoriented. Some of the subjects experiencing a reorientation illusion were convinced that they and the room had remained upright throughout the experiment. We had to show them the room rotating to convince them that they had not remained vertical. A few subject is each condition were so confused that they could not respond to our questions or make consistent settings of the rods. It should be possible to discover which category trainee pilots fall into. A simple test would be to place them in a supine posture inside a room or cabin inclined 90° and see whether they experience a reorientation illusion. Perhaps the most dangerous category is that of being confused because a confused person cannot apply any corrective strategies. A person who uses the visual frame of reference rather than gravity can be trained to realize the error and apply corrective strategies.

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14 ABSTRACT

(U) Spatial disorientation has been identified as major causes of aviation accidents. One cause of spatial disorientation is an aftereffect of returning the body to a vertical posture after having maintained it for some time in a non-vertical posture. However, investigations into the nature of these aftereffects have frequently produced conflicting results. The experiments in Part A of the current study were designed to resolve several controversial issues by examining the effects of duration of body tilt and speed of return to vertical on the setting of a tactile rod to vertical. Judgments of tactile vertical became more erroneous as the duration of the adaptation tilt increased. Importantly, while tactile vertical was overestimated when subjects were held at the adaptation tilt, it was underestimated following their rotation back to vertical or 10_1 from vertical. This finding suggests that two distinct processes are involved in errors of the subjective vertical—one based on aftereffects of subjecting the otolith organs to a displaced direction of gravity and another based on aftereffects of rotary acceleration acting on the vestibular canals.
A second cause of disorientation in pilots arises from conflicts between information from the gravity sense organs and from vision. The experiments in Part B were designed to investigate the relative contributions of three frames of reference to judgments of self orientation to gravity. The first frame of reference is gravity, as sensed by the gravity sense organs (otolith and tactile/proprioceptive sense organs). The second frame of reference is the body axis and the third is the perceived tops and bottoms of familiar objects in the visual scene. I recently discovered that about 50% of adults feel upright in an upright room when in fact they are lying on the back looking at a wall of the room above them. This is similar to the situation in which a pilot in a banked or inverted aircraft feels upright in an upright aircraft. Experiment B1

was designed to measure the incidence of this type of reorientation illusion for each orientation of the body (erect, supine, prone, and recumbent) and each orientation of the visual surroundings. Reorientation illusions occurred in all condition except those in which the visual scene was upright. They occurred most often when the body was at the same angle to gravity as the visual scene, as when a pilot rotates with a rolling aircraft. There was very little evidence that people used their own body to judge the direction of gravity. There were large individual differences. Some people relied heavily on the visual scene while others relied on their gravity sense organs and ignored conflicting information from the visual scene.
We noticed that younger people were less prone to disorientation illusions and decided to investigate the effect of age. In Experiment B2 we determined the incidence of static and dynamic reorientation illusions in subjects ranging in age from 9 to 78 years. Ninety percent of subjects of all ages experienced the dynamic reorientation illusion when viewing a moving scene but the percentage of subjects experiencing static reorientation illusions increased with age. We propose that the dynamic illusion depends on a primitive mechanism of visual-vestibular interaction but that static reorientation illusions depend on learned visual cues to the vertical arising from the perceived tops and bottoms of familiar objects and spatial relationships between objects. Older people become more dependent on visual polarity to compensate for loss in vestibular sensitivity.

15 KEYWORDS, DESCRIPTORS or IDENTIFIERS

(U) Attitude Perception, Rolling manoeuvre